PROJECT TECHNICAL REPORT

TASK E-9G

LUNAR FAR SIDE COMMUNICATIONS COVERAGE AND VISIBILITY ANALYSIS FOR SATELLITE RELAY SYSTEMS

NAS 9-8166

5 February 1970

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

Prepared by

Communications and Sensor Systems Department
Electronics Systems Laboratory

TRW
SYSTEMS GROUP

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ILLUSTRATIONS

1.0 INTRODUCTION

A comprehensive lunar exploration program should naturally proceed from the present efforts concentrated on the earth side to landings on the far side of the moon. Because the far side is never visible from the earth, communications with a lunar far side terminal from earth (or a point on the near side of the moon) will involve some form of intermediate relay. The requirements for such a relay are already apparent in the current Apollo missions since the orbiting CSM and LM experience a loss of communications when passing behind the moon. This restriction of communications is serious because of critical operations (such as SPS ignition for insertion on the return to earth trajectory) which occur behind the moon. Real time communications to the lunar far side become a prerequisite for far side landings and exploration. It should be noted, however, that at present, these are no firm plans for such a far side mission.

The work summarized in this report considers the lunar far side communications problem. Following a review of current and projected communications requirements, the use of lunar orbiting satellites is investigated with respect to coverage and visibility.

1.1 STUDY PLAN

This report documents the coverage and visibility analysis for lunar orbiting communications satellites. This study is a part of an overall system study for a lunar far side satellite relay communications system.

The overall study plan is illustrated schematically in Figure 1 . Following a brief requirements survey, and the coverage and visibility analysis reported herein, the study program encompasses three tasks:

(1) Communications system parametric analysis

(2) Trajectory and vehicle considerations

(3) Survey of applicable technology

The communications system parametric analysis is based upon a mathematical model of a satellite communications system. Requirements for relay satellite

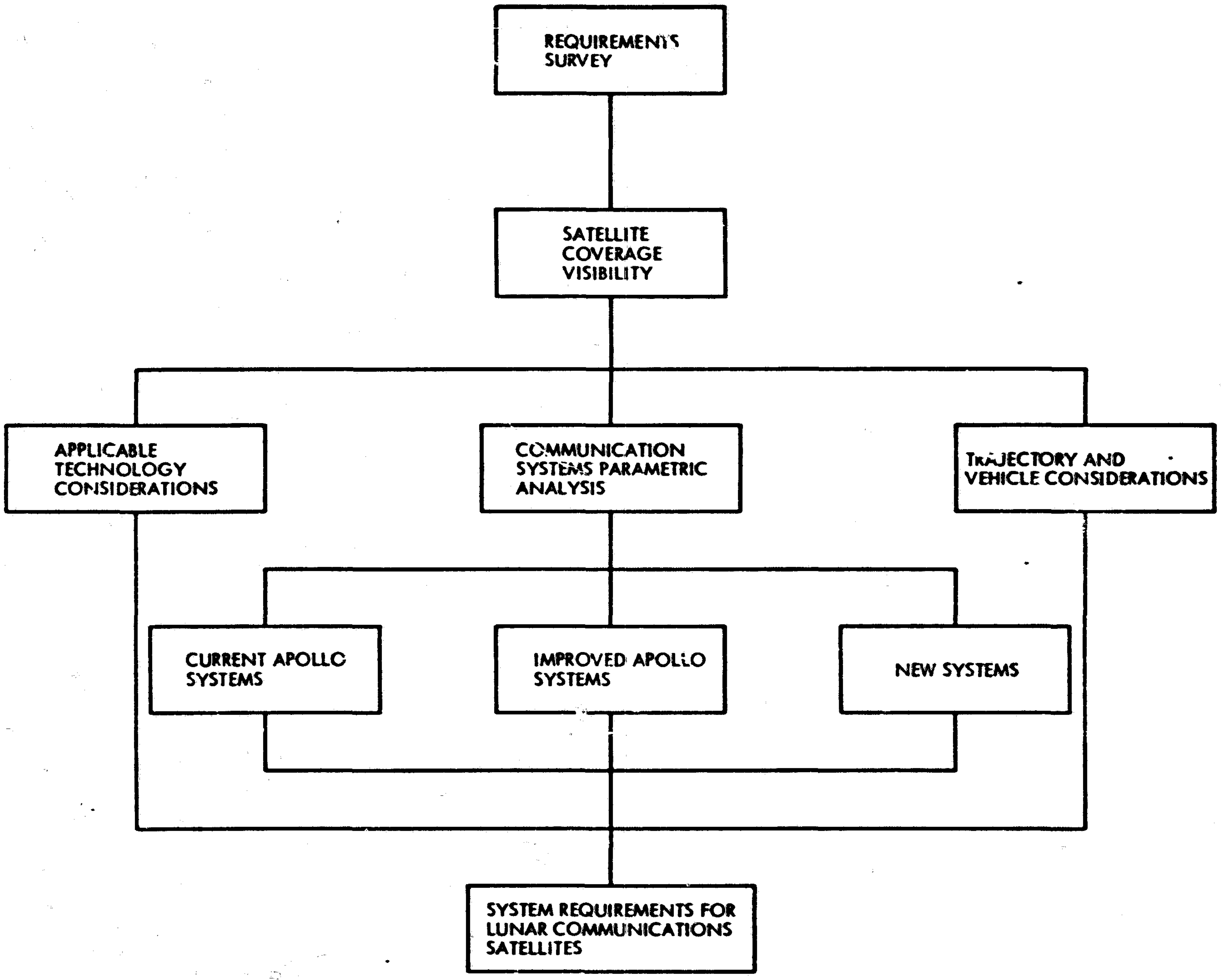


FIGURE 1. PROGRAM PLAN

system parameters such as effective radiated power, noise, temperature, etc., are being investigated for three types of lunar terminal:

(1) Current Apollo systems

(2) Improved Apollo systems

(3) New communications terminals

Trajectory and vehicle considerations include performance, trajectory, and guidance analysis which encompass,but are not limited to,the following major items:

(1) ΔV requirements for entering selected lunar orbits

(2) Payload capabilities of candidate launch vehicles

(3) Perturbative effects on selected lunar orbits

(4) Propulsion requirements for orbit stabilization

(5) Methods of deploying multiple satellites from a single launch vehicle.

The survey of applicable communications satellite technology is directed toward an assessment of the current state-of-the-art in the major system over such as tracking antenna design, rf power capabilities, reliability, etc.

As indicated on the diagram, the results of these analyses will be integrated into a definitive statement of system requirements for a lunar communications satellite system. These requirements, based upon firm supporting analyses, would be the point of departure for a preliminary design of a lunar communications satellite.

1.2 COMMUNICATIONS REQUIREMENTS

It is instructive to briefly examine the communications requirements for the current Apollo missions and to estimate projected communications requirements for possible future lunar exploration. A summary of these requirements is shown in Table I. Note that only the first two entries on Apollo G-H missions and Apollo J missions are firm requirements at the present. The remaining entries are the author's projections. As shown in the Table, it is expected that initial far side Apollo missions would closely parallel the near side activities currently planned. Initial far side exploration would then require communications relay to earth from single lunar surface terminals (LM, rovers) whose location and surface activity time would be known well in advance of the mission. As will be discussed later, knowledge of mission time and landing site have substantial impact on relay communication system design.

Beyond Apollo type missions, one might expect future lunar surface explorations to involve the establishment of a near side lunar base, followed by a system of near side bases. This in turn might be followed by an initial far side base and possibly a system of far side bases. Wide ranging surface exploration from this base or system of bases might include long range EVA using large mobile surface laboratory vehicles. Finally, a lunar orbiting space station/base might be established.

This brief discussion has thus indicated that the goal of any lunar communications system should be coverage of the entire lunar sphere all the time. Transmission requirements start with those of the current Apollo system and proceed to those associated with comprehensive systems of bases and orbiting stations. One might expect these latter requirements to be similar to those projected for earth orbiting space bases, i.e., multiple two-way TV channels, high data rate telemetry channels, multiple channel EVA communications, etc.

While the long term goals are complete and continuous coverage, the time phasing of the operational requirements is such that the establishment of a lunar far side relay communications system may be phased in concert with developing requirements. It is important to note that the communications relay systems required to support initial Apollo missions would be substantially less complicated than the full coverage system.

Table 1. Communications Summary for Lunar Exploration

Phase of Lunar Exploration	Surface Stay Time	Activities	Communications Requirements		Remarks
			Possible Modes	Possible Links	
Current Apollo Missions* (G-H type missions)	up to 35 hrs	Limited EVA within 1500 ft. of LM - duration 2 hrs. 40 minutes	USB-voice	LM-CSM	See mission time line.
Apollo Earth-side Lunar* Exploration Missions (J-type missions)	up to 78 hrs	Expanded walking EVA within 1-2 KM of LM for 3 hrs. 40 minutes Mobile EVA within 5 KM of LM using rover	USB-voice USB-data USB-TV USB-ranging VHF-voice VHF-data VHF-ranging	LM-CSM LM-EVA LM-earth CSM-earth Rover-CSM Rover-LM Rover-earth Rover-EVA	See mission time line
Initial Far Side Apollo Missions	Short similar to G-H missions	Limited EVA similar	USB-voice USB-data USB-TV USB-ranging VHF-voice VHF-data VHF-ranging	LM-CSM LM-EVA LM-earth CSM-earth	No far side missions planned before 1975 at present
Apollo Far Side Lunar Exploration Missions	Similar to J-type missions	Expanded EVA similar to J-type missions	USB-voice USB-data USB-TV USB-ranging VHF-voice VHF-data VHF-ranging	LM-CSM LM-EVA LM-earth CSM-earth Rover-CSM Rover-LM Rover-earth Rover-EVA	

*Reference: "Program and Mission Definition Apollo Lunar Exploration" NASA/MSC Report No. SPD-9P-052 August 15, 1969.

Table 1. Communications Summary for Lunar Exploration - Continued

Phase of Lunar Exploration	Surface Stay Time	Activities	Communications Requirements: Possible Modes	Communications Requirements: Possible Links	Remarks
Initial Lunar Base	Indef-inite	Comprehensive surface science and exploration. Long duration EVA using large surface rovers.	Voice Data TV Ranging	Base-orbiters Base-EVA Base-rovers Orbiters-earth	Post 1975
System of Lunar Bases	Indef-inite	Multiple sites for comprehensive surface science and exploration.	Voice Data TV Ranging	Base-orbiters Base-EVA Base-rovers Base-earth Inter-base links	Post 1975
Lunar Orbiting Space Station		Similar activity to earth orbiting space station	Voice Data TV Ranging	Station-earth Station-orbiters Station-lunar Station-surface Station-terminals Station-EVA	Post 1980

2.0 METHODS FOR LUNAR FAR SIDE COMMUNICATIONS RELAY

There are a variety of possible methods for relay communications from the far side of the moon. These possibilities are briefly summarized in the discussions below.

One approach is that of providing a lunar surface link from a far side terminal to a near side terminal with subsequent relay to an earth station. The surface mode of transmission could be one or a combination of the following techniques:

(1) Lunar surface point-to-point relay

a. Microwave

b. VHF or UHF radio relay

(2) Surface wave transmission (generally limited to frequencies below the high frequency region of the spectrum)

While attractive for special applications, the relay mode is primarily limited by the difficulty and expense of establishing a sufficiently extensive network to provide area coverage for the lunar far side. The surface wave transmission mode can provide area coverage, but because of the frequency limitation can provide limited information bandwidth. This mode is, however, very attractive for backup communications, and is also attractive for specific applications where wide bandwidth is not a primary consideration. For example, far side experiment packages with low data rates might use this mode for relaying scientific information to a near side terminal with subsequent relay to an earth station.

Lunar communications satellites provide the most direct method of complete area coverage for the lunar sphere. These are basically three configurations for such satellites

a. Lunar orbiting satellites

b. Libration point satellite at position L_2

c. A "Hummingbird" lunar synchronous satellite

There is no stable synchronous orbit for the moon due to the effect of the earth's potential. A lunar synchronous orbit would be possible in principle using continuous propulsion on board the satellite. This concept has been investigated by GSFC (Reference 1).

It should be noted, also, that passive or active relay satellites are possible in this application. Terminal effective radiated power limitations are such that only active relay satellites represent practical possibilities. Coverage and visibility observations developed in this report, however, apply to both active and passive satellites.

This report specifically considers the coverage and visibility factors for a lunar orbiting system of communications satellites. Since the characteristics on the L_2 libration point are well documented, (Reference 2) no specific attention has been devoted to the coverage and visibility analysis for this type of satellite.

It should also be noted that only circular orbits are considered. A special highly elliptical earth orbit which has an apogee behind the moon is being considered and will be described in a subsequent report.

3.0 SATELLITE RELAY SYSTEMS

The use of lunar orbiting communications satellite offers an attractive solution to the problem of lunar far side communications. The technology of communications relay by satellite is well advanced through the current efforts in terrestrial applications. Relay of communications from spacecraft to ground terminals is being actively explored through the planned ATS-F and ATS-G experiments and the initial work on geosynchronous tracking and data relay satellites (TDRS).

3.1 COVERAGE OF THE LUNAR SURFACE

The basic problem in the design of a satellite communications network is that of providing adequate coverage. The most optimistic goal would be a system where any lunar surface terminal or any vehicle in lunar orbit could communicate with earth at any time. Due to the evolutionary nature of the lunar exploration program as it is currently defined or projected, it may neither be practical or desirable to attempt to achieve this goal with the initial efforts in providing lunar far side communications relay. For initial Apollo-type far side missions, it will only be necessary to provide coverage during short periods of a few days at infrequent intervals.

A second factor of interest is the desirability of eliminating requirements for satellite-to-satellite relay. This factor has a substantial impact upon the design of a communications satellite system. For example, if the line of sight path from earth to the communications satellite visible from the lunar far side terminal is occulted by the moon, then there is no possibility of direct relay to earth, and a second relay link through a satellite would be required. This satellite-to-satellite relay mode imposes severe requirements upon the communications system. The studies described in this report will assume that no satellite-to-satellite relay is to be provided.

3.1.1 Choice of Orbit for the Communications Satellite Network

It is impossible to cover all points on the lunar sphere simultaneously from satellites in a single orbital plane. The degree of coverage varies with the altitude of the satellite orbit, the number of satellites and the minimum elevation of the satellite above the horizon viewed from the lunar surface at acquisition. For example, if a lunar equatorial orbit is utilized then the polar regions will never be covered. An inclined orbit will allow coverage of all points on the lunar surface, but not simultaneously. A system of polar orbits is probably the most promising candidate for realizing the long term goal of 100% coverage of the lunar surface 100% of the time. An equatorial orbit may be most effective, however, if all Apollo missions operate over a region confined to latitudes of, say, $\pm 40°$ of the lunar equator. In summary, the choice of orbit rests upon projected operational requirements. Subsequent discussion on the orbital configuration of candidate communication satellite systems will be directed toward three objectives:

(1) A single system of equatorial satellites oriented toward support of current Apollo missions.

(2) A system of polar orbiting satellites oriented toward the long term goal of 100% coverage for any time.

(3) A system for partial coverage to support Apollo or other specific missions.

3.2 BASIC COVERAGE CONSIDERATIONS

Consider the geometry illustrated in Figure 2. A system of N satellites is to be positioned in circular orbit about the moon to provide communications between points on earth and terminals on the lunar surface as well as vehicles in orbit around the moon. In order to provide continuous communications with lunar terminals, some overlap in coverage must be provided in the orbital plane of the communications satellites. It is convenient to measure this overlap in terms of the selenocentric angle α as shown in Figure 2. The third parameter of interest is the elevation angle at acquisition, ϵ. This is the angle above the horizon viewed from the lunar terminal at which the acquisition of a signal from the communications satellite could first be accomplished. There are therefore, three independent quantities which determine the altitude of the circular orbits of the communications satellite network

(1) Number of satellites, N.

(2) Selenocentric angle of overlap for coverage in the orbital plane, α.

(3) Elevation angle at acquisition ϵ.

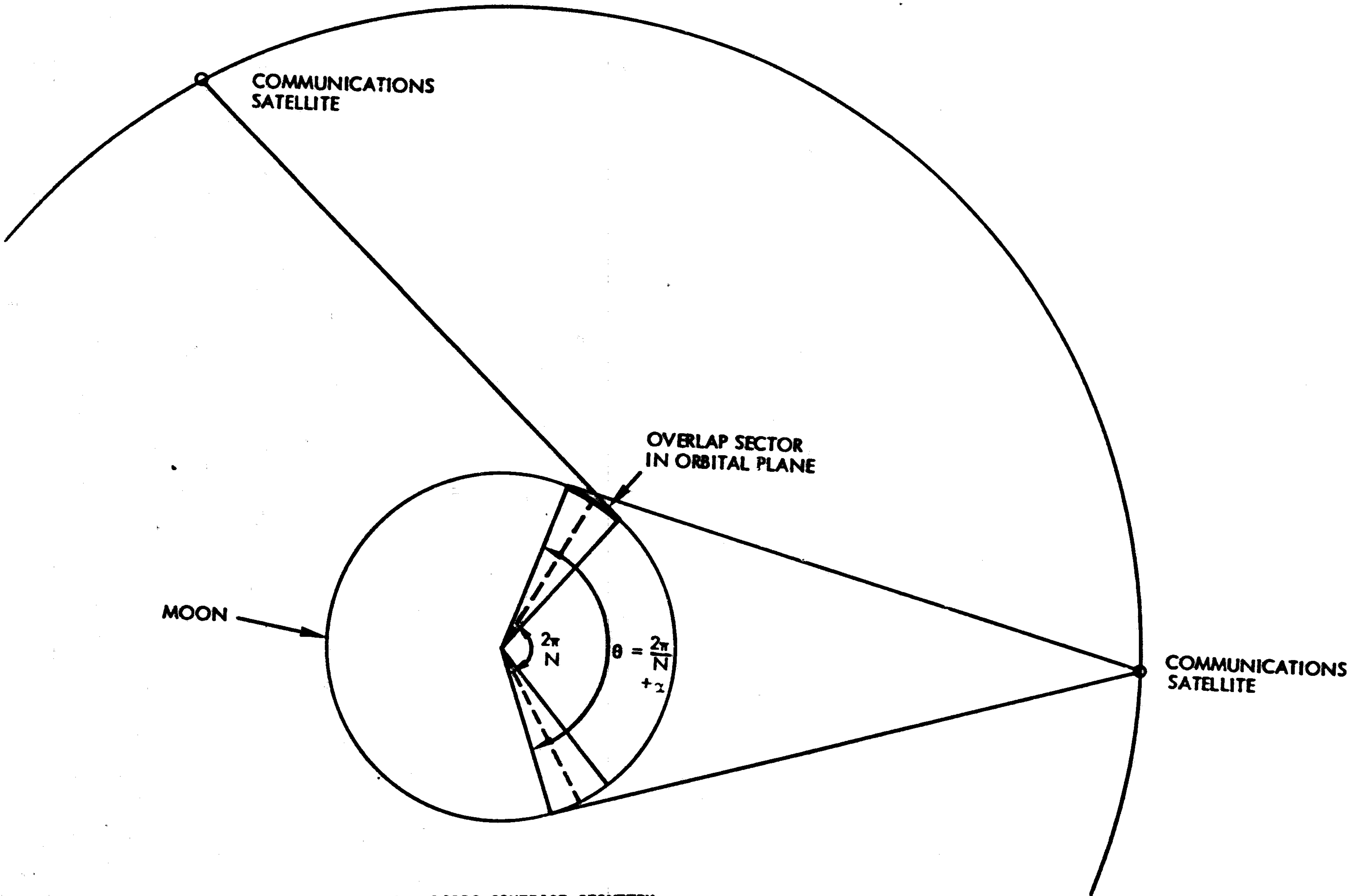


FIGURE 2. BASIC COVERAGE GEOMETRY

Referring to the simplified diagram of Figure 2 , the law of sines may be applied to obtain

$$\frac{\sin\left(\frac{\pi}{N} + \frac{\alpha}{2}\right)}{D} = \frac{\sin\left(\frac{\pi}{2} + \epsilon\right)}{R_M + h} = \frac{\sin\theta}{R_M} \qquad (1)$$

where:

R_M = radius of moon

h = altitude of communications satellite above the lunar surface

D = communications distance at acquisition

The angle θ may be expressed in terms of the other angles as follows

$$\theta = \pi\left(\frac{1}{2} - \frac{1}{N}\right) - \left(\varepsilon + \frac{\alpha}{2}\right), \; N \geq 3 \qquad (2)$$

Using (2), it is easily shown from (1) that the satellite altitudes is given by

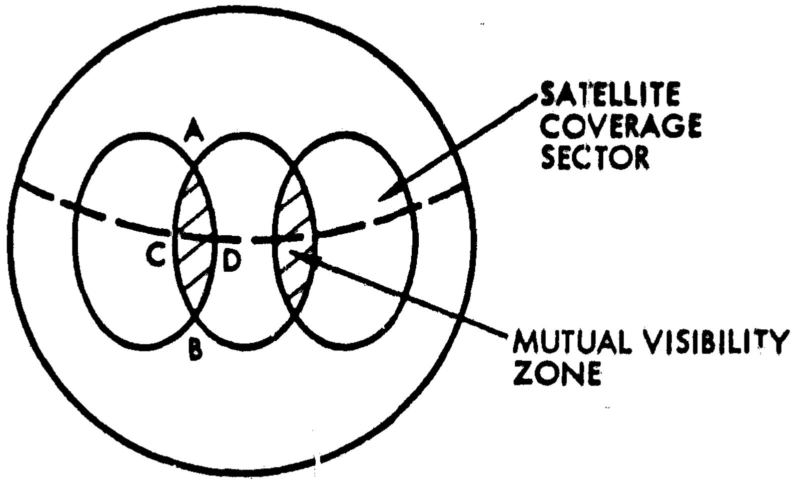
$$h = R_M \frac{(\cos\varepsilon - \sin\theta)}{\sin\theta} \qquad (3)$$

The maximum communications distances will be

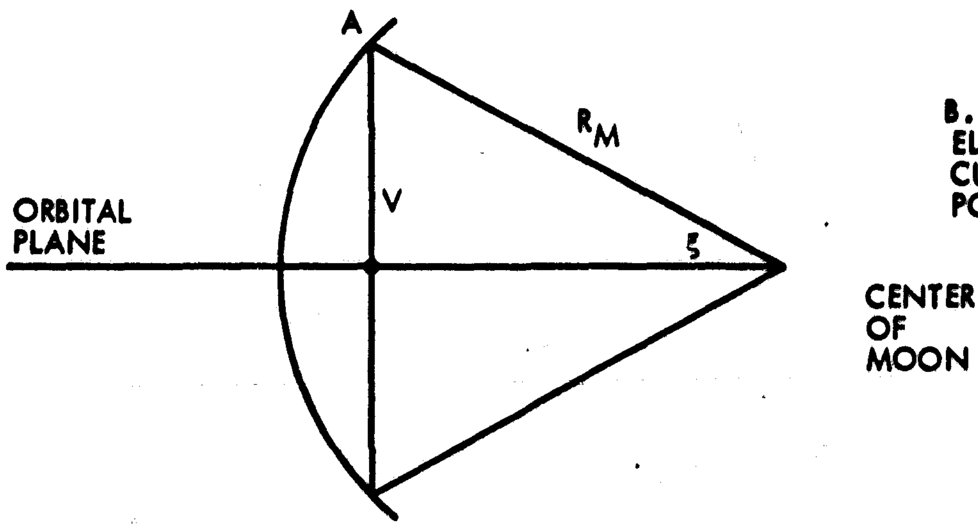
$$D = R_M \frac{(\sin \frac{\pi}{N} + \frac{\alpha}{2})}{\sin\theta} \qquad (4)$$

3.3 DERIVATION OF EXTENT OF MUTUAL VISIBILITY ZONES

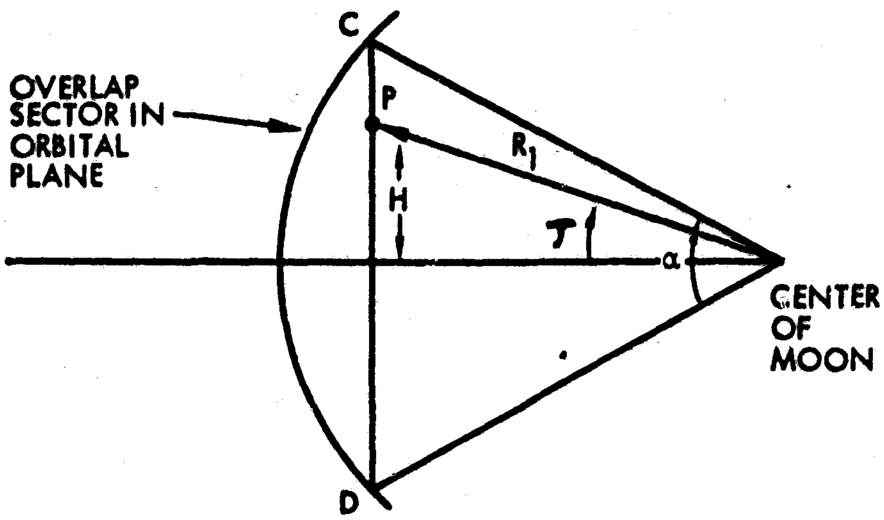
The requirement of continuous communications dictates that a period of mutual visibility must be provided for two communications satellites and the lunar terminal. Specification of a selenocentric angle of overlap for coverage in the orbital plane of communications satellites meets this requirement. It is of interest to determine the extent of this mutual visibility region. The mutual visibility regions for adjacent satellites is illustrated in Figure 3.. Figure 4 illustrates the orientation of the intersection of the cone representing the satellite coverage sector and the



B.1 (a) MUTUAL VISIBILITY ZONES



B.1 (b)
ELEVATION
CUT THROUGH
POINTS A AND B



B.1 (c)

AZIMUTHAL CUT
THROUGH C AND D

FIGURE 3. MUTUAL VISIBILITY ZONES

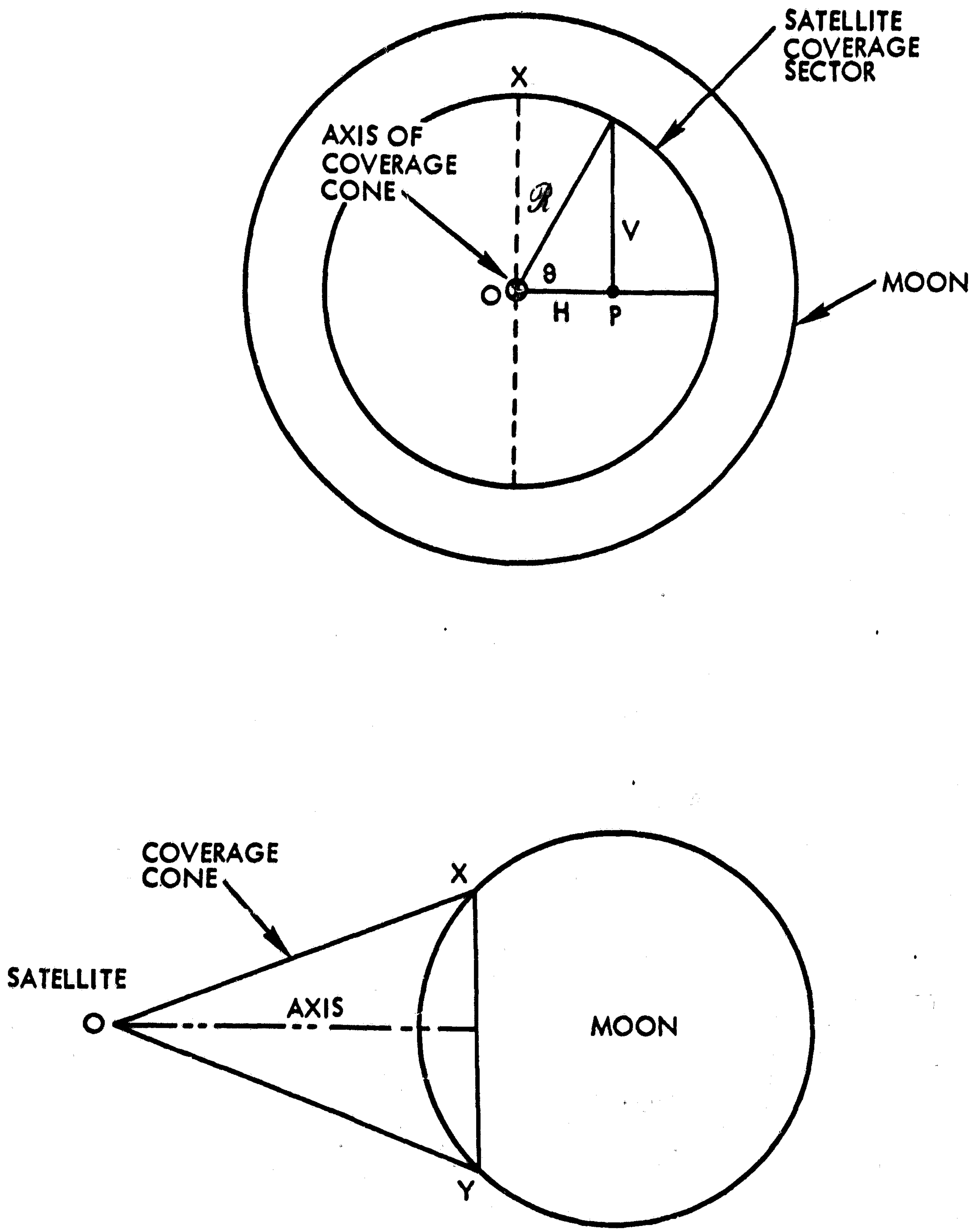


FIGURE 4. ORIENTATION OF SATELLITE COVERAGE SECTOR

lunar sphere. Referring to these diagrams it may be seen that the radius R is related to the lunar radius by

$$R = R_M \sin\left(\frac{\pi}{N} + \frac{\alpha}{2}\right) \tag{5}$$

where:

R_M = lunar radius

N = number of satellites ($N \geq 3$)

α = seleconcrentric angle of overlap for coverage sectors in orbital plane of satellites.

If the center line of the right circular coverage cone is taken as reference, then the angular coordinates (τ, ξ) define the intersection of the coverage cone with the lunar sphere. For example, if an equatorial system of communications satellites is being considered, then τ will be the longitudinal coordinate from the centerline of the coverage cone, which ξ will be the latitudinal coordinate for the intersection. These coordinates for every point on the intersection are conveniently expressed in terms of the angle θ shown in Figure 4. It may be seen that

$$\begin{aligned} V &= R \sin \theta \\ H &= R \cos \theta \end{aligned} \tag{6}$$

and,

$$R_1 = R_M \cos \xi$$

$$\sin \tau = \frac{H}{R_1} \qquad\qquad \sin \xi = \frac{V}{R_M} \tag{7}$$

Using (6) - (7) the angles τ and ξ may be determined to be

$$\begin{aligned} \xi &= \sin^{-1} \left\{\sin \left(\frac{\pi}{N} + \frac{\alpha}{2}\right) \sin \theta\right\} \\ \tau &= \sin^{-1} \left\{ \frac{\sin \left(\frac{\pi}{N} + \frac{\alpha}{2}\right) \cos \theta}{\cos \xi} \right\} \end{aligned} \tag{8}$$

Of particular interest is the angle ξ at which the coverage zones intersect since this is the maximum extent of the mutual visibility zone. Figure 5 illustrates the geometry to be considered in determining this angle. The orbital plane of the satellites in Figure 5 is the plane of the paper. Figure 6 is a vertical cut in the plane of OV shown in Figure 5. From triangle OXR it is seen that

$$OR = R_M \cos\left(\frac{\pi}{N} + \frac{\alpha}{2}\right) \qquad (9)$$

while from triangle OVR, it may be determined that

$$OV = OR \sec\frac{\pi}{N} \qquad (10)$$

and

$$OV = R_M \cos\left(\frac{\pi}{N} + \frac{\alpha}{2}\right) \sec\frac{\pi}{N} \qquad (11)$$

The central angle for the point of intersection is then

$$\xi_{intersection} = \cos^{-1}\left\{\cos\left(\frac{\pi}{N} + \frac{\alpha}{2}\right) \sec\frac{\pi}{N}\right\} \qquad (12)$$

The extent of the mutual visibility region in fact determines the effective coverage limits for a system of equally spaced coplanar satellites. Figure 7 illustrates these coverage limits. Note that there are two regions where there is no continuous communications coverage. The extent of these regions is determined by interdependent quantities such as the altitude of the relay satellite network, number of satellites, and required elevation angle at acquisition. Figure 8 illustrates the dependence of the selenocentric angle subtended by the coverage region for systems of three, and six satellites upon the selenocentric angle of coverage overlap in the orbital plane of the satellites.

The impact of this coverage limitation is obvious for an equatorial system of lunar communications relay satellites. As will be discussed

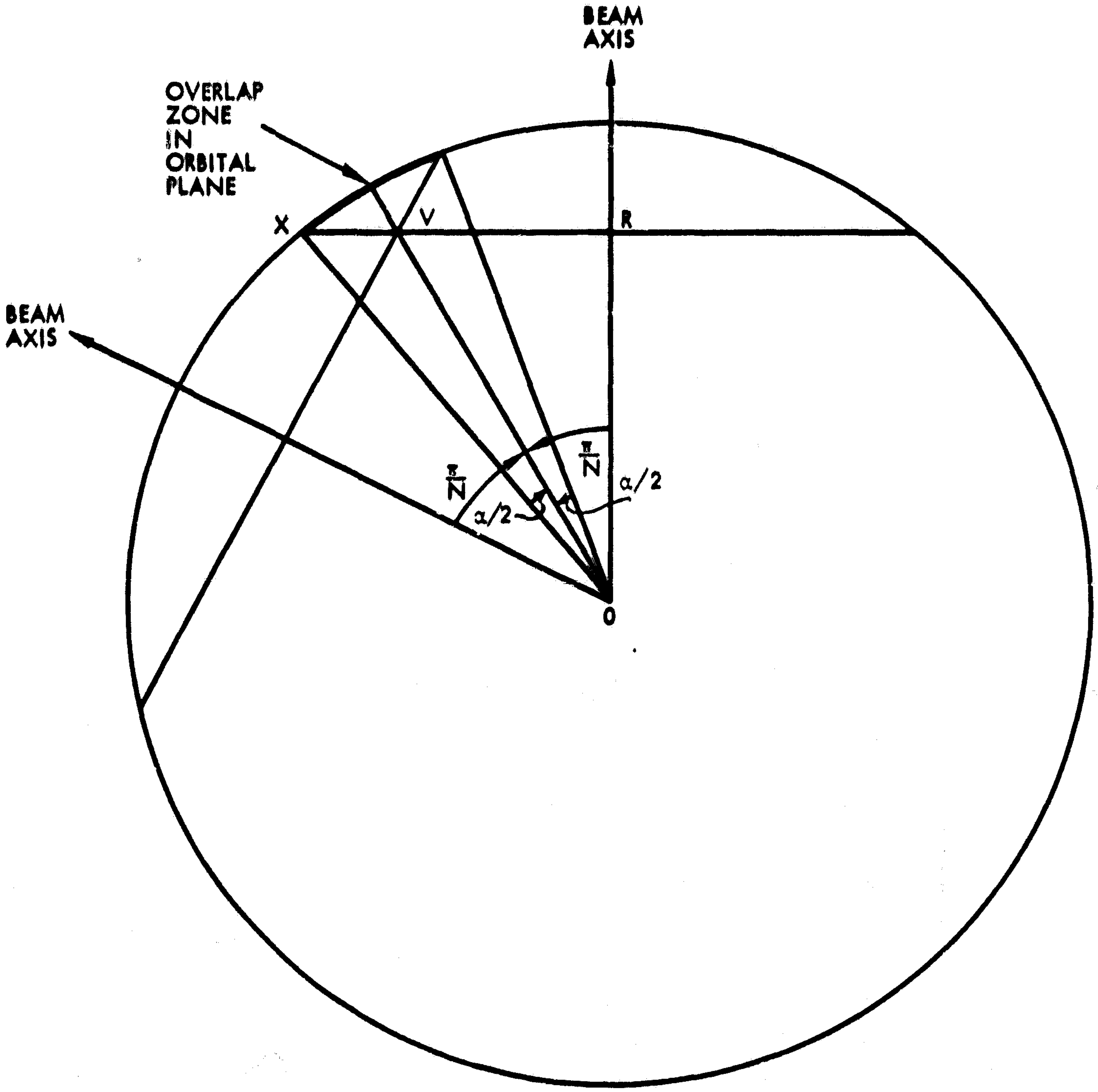


FIGURE 5. GE/METRY PERTINENT TO OUT-OF-PLANE COVERAGE ANALYSIS

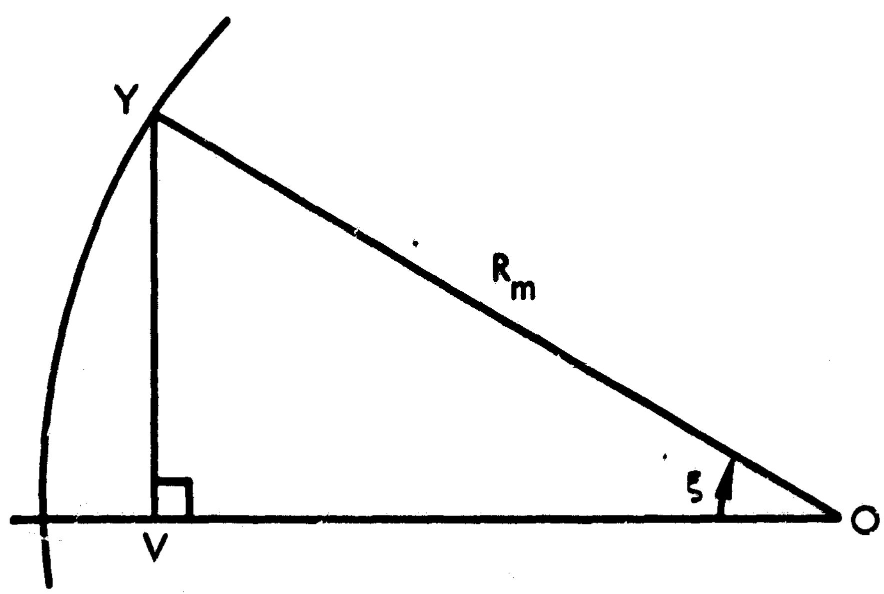


FIGURE 6. VERTICAL CUT THROUGH POINTS O AND V OF FIGURE 5.

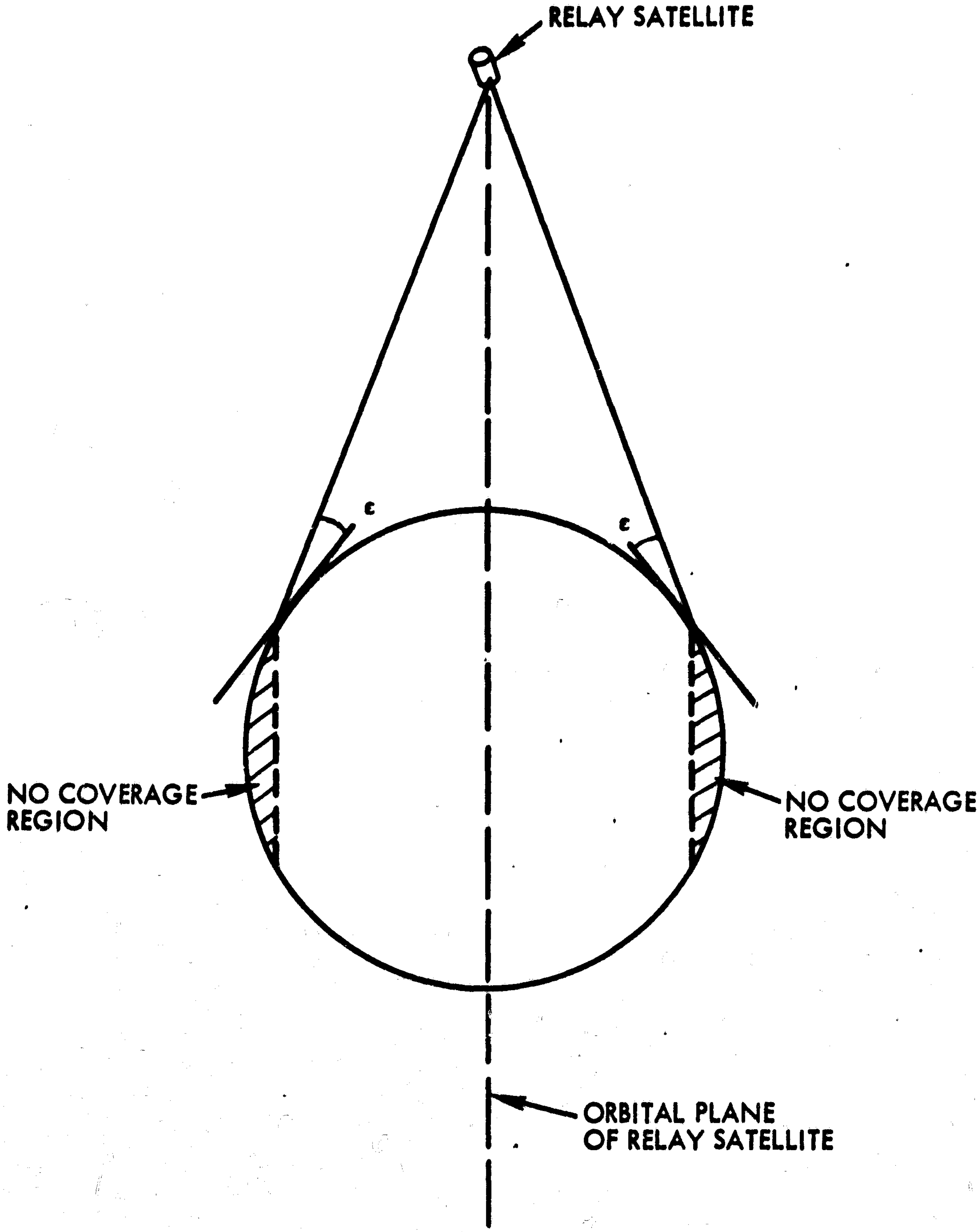


FIGURE 7. COVERAGE RESTRICTION DUE TO PROVISION OF NON-ZERO ELEVATION ANGLE AT ACQUISITION

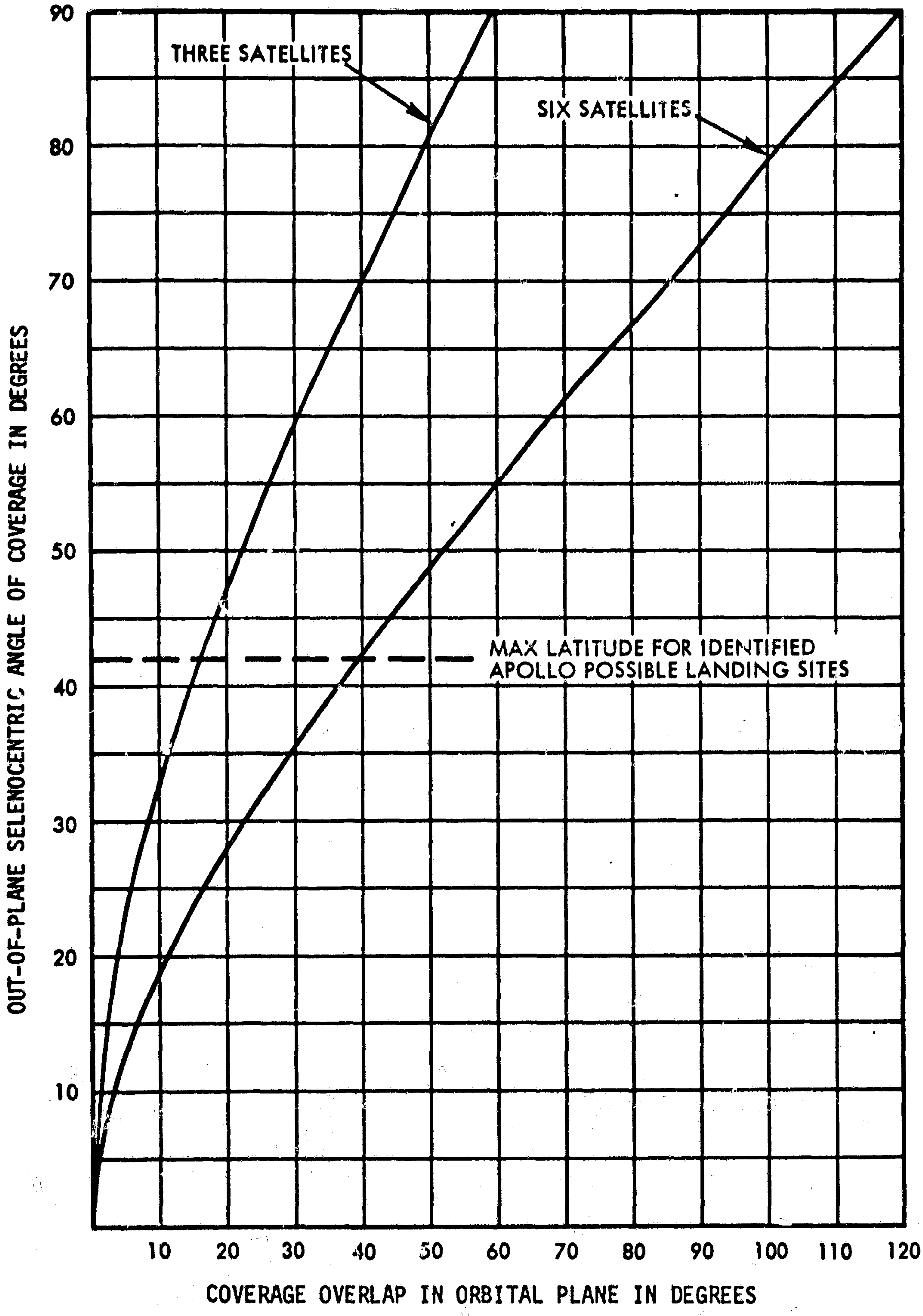


FIGURE 8. OUT-OF-PLANE COVERAGE FOR SELECTED SATELLITE SYSTEMS

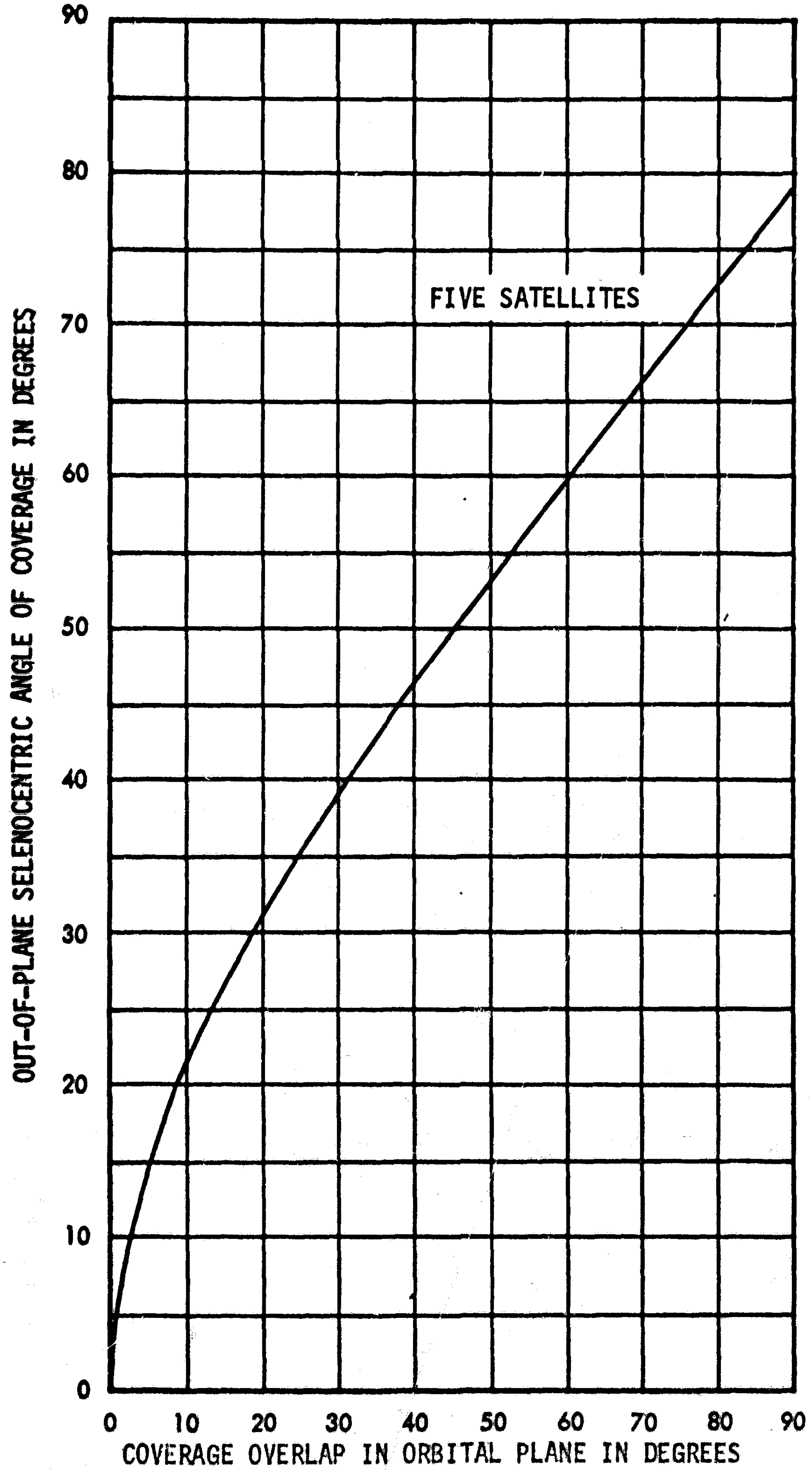


FIGURE 9. OUT-OF-PLANE COVERAGE FOR SELECTED SATELLITE SYSTEMS

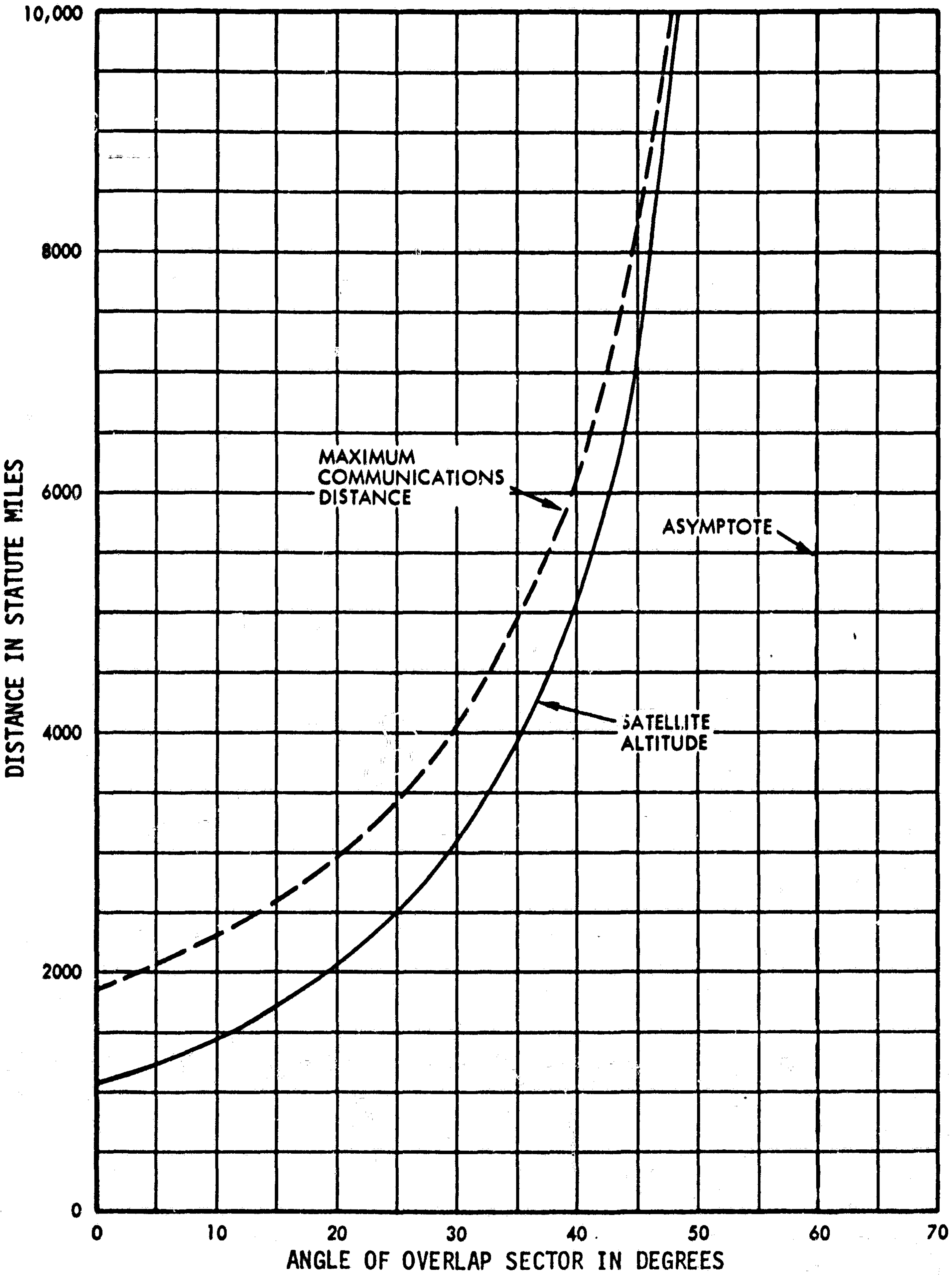


FIGURE 10. SATELLITE ALTITUDE AND MAXIMUM COMMUNICATIONS DISTANCE IS. ANGULAR OVERLAP SECTOR FOR THREE (3) EQUI-SPACED SATELLITES IN CIRCULAR ORBIT

ELEVATION ANGLE AT ACQUISITION IS 0°

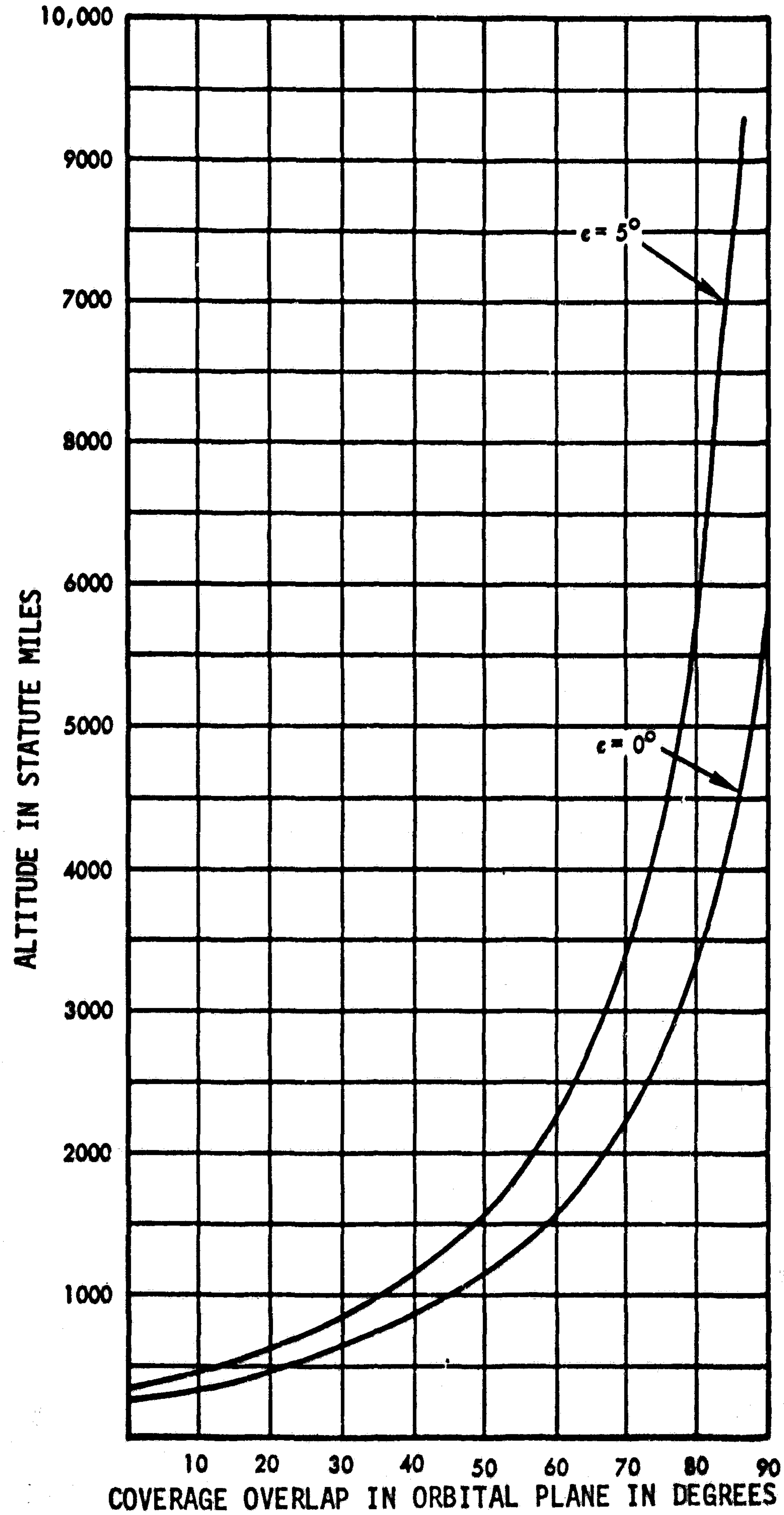


FIGURE 11. ORBITAL ALTITUDE VS. SELENOCENTRIC ANGLE OF COVERAGE OVERLAP FOR FIVE EQUI-SPACED COPLANAR SATELLITES IN CIRCULAR ORBIT

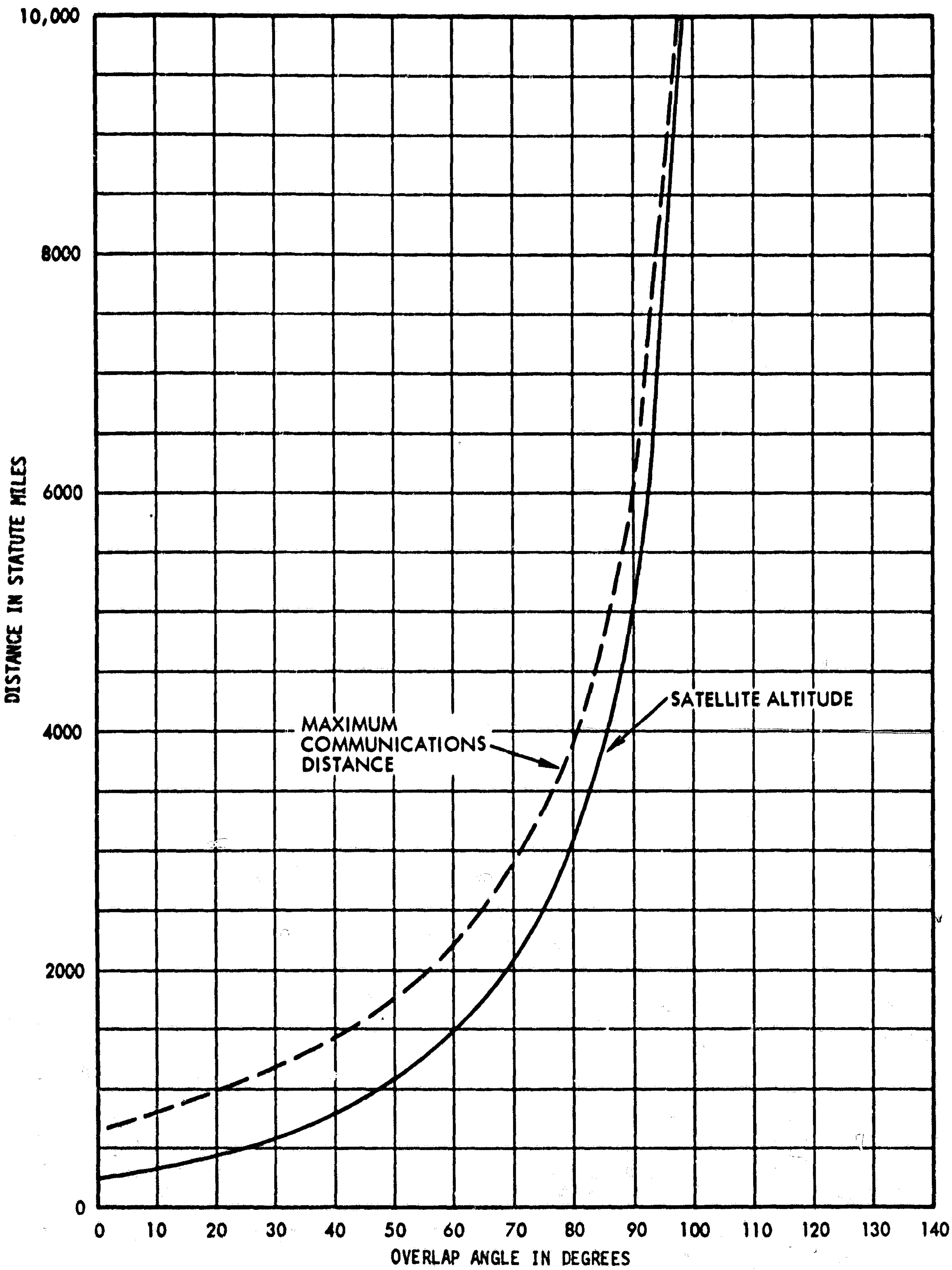


FIGURE 12. SATELLITE ALTITUDE VS. OVERLAP SECTOR FOR SIX (6) EQUI-SPACED SATELLITES

$\varepsilon = 5°$

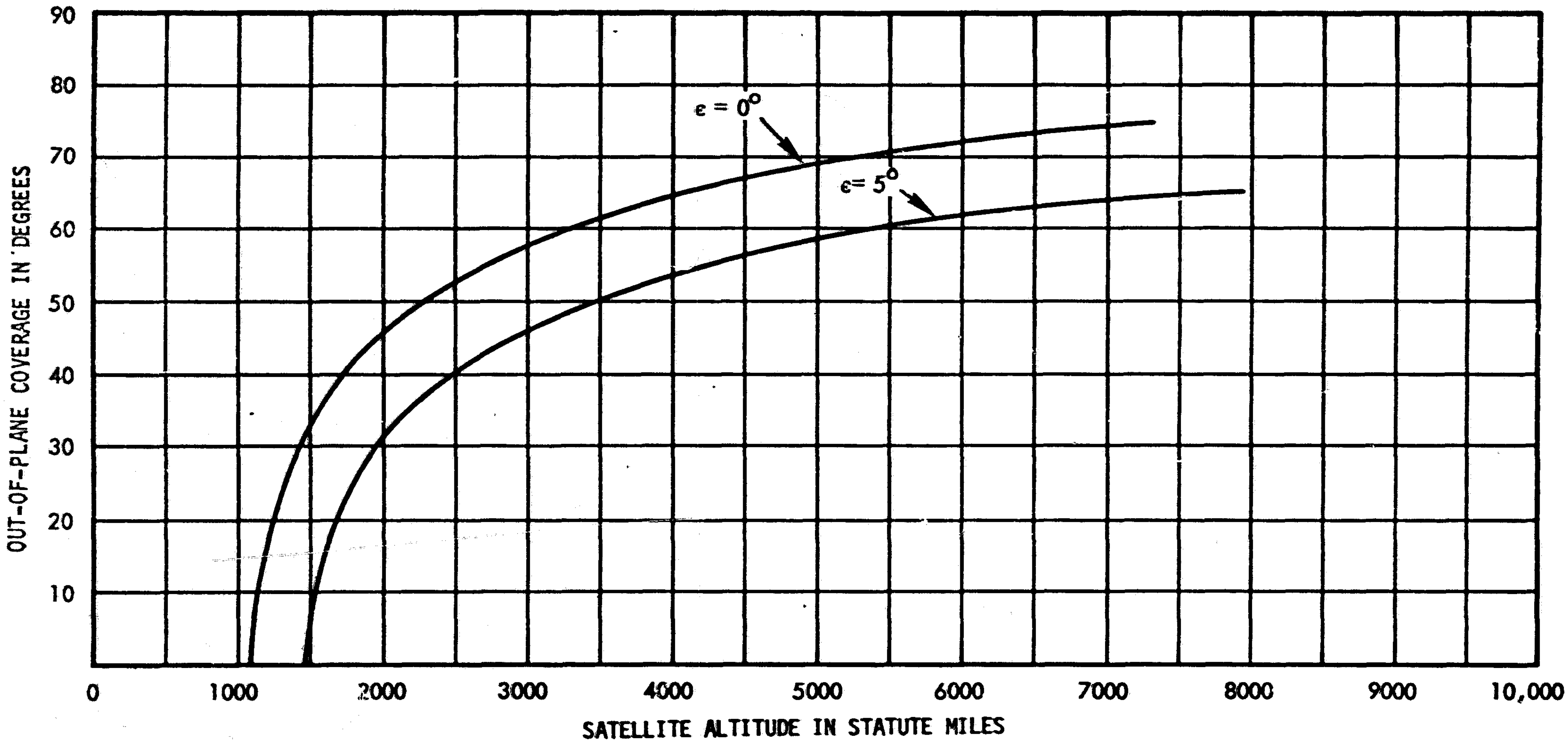


FIGURE 13. OUT-OF-PLANE COVERAGE FOR THREE SATELLITES EQUI-SPACED IN CIRCULAR LUNAR ORBIT

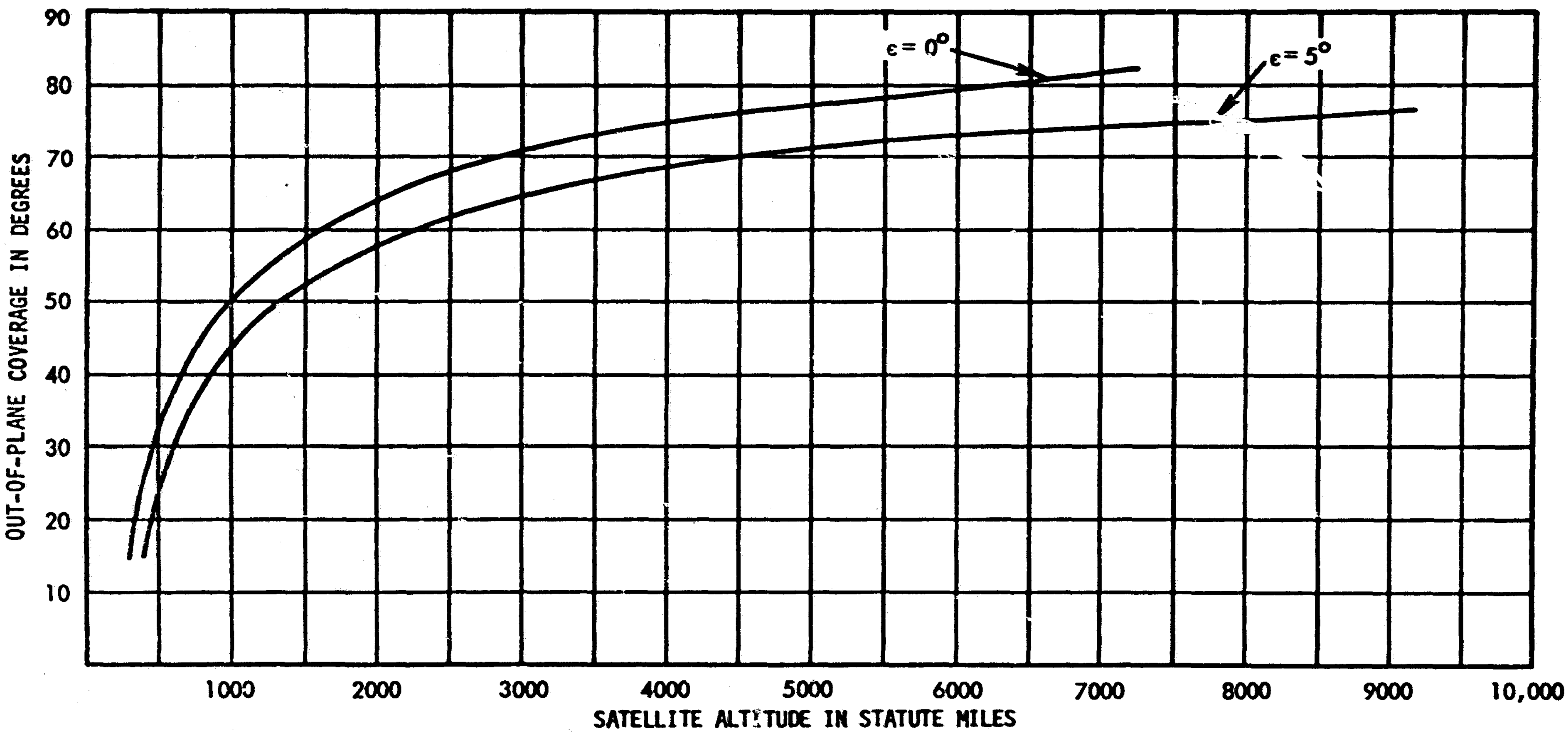


FIGURE 14. OUT-OF-PLANE COVERAGE FOR FIVE SATELLITES EQUI-SPACED IN CIRCULAR LUNAR ORBIT

in a subsequent section of this report, this factor also imposes a requirement for three non-coplanar sets of polar orbiting satellites if continuous coverage of the entire lunar surface is to be achieved.

Figures 9 - 14 illustrate the dependence of satellite altitude and surface coverage for selected systems.

3.4 AN EQUATORIAL SYSTEM OF COMMUNICATIONS SATELLITES

An equatorial system of satellites for lunar far side relay applications is limited by two factors:

(1) Each of the communications satellites is occulted by the moon during each orbital period.

(2) Coverage of extreme polar regions of the moon is possible.

The first of these limitations may be overcome by providing a sufficient number of satellites properly phased in equatorial orbit. The second limitation is impossible to counter using only satellites in lunar equatorial orbit.

To further illustrate this first observation, consider the diagram of Figure 15. An equatorial system of five satellites is shown, and this system is arranged to provide uninterrupted service for a point on the lunar far side located in the plane of the orbit of the satellite network. This uninterrupted service is possible because of the complete overlap in coverage between adjacent satellites in the system.

For example, if the lunar far side surface terminal is located at point T, and the earth-moon orientation is as shown on the diagram of Figure 15, then satellite 1 will not be visible from earth. Satellite 5 will be passing out of view of the surface terminal while satellite 2 is just coming into view. Relay may thus be accomplished using 2 until 1 emerges from the occultation zone.

Note that uninterrupted service is possible only for points in the orbital plane. In order to provide this service to points out of plane, more than the indicated amount of overlap would be required. Note also that five satellites on the minimum number for uninterrupted service in the orbital plane since four or less cannot be arranged so as to provide complete overlap in plane.

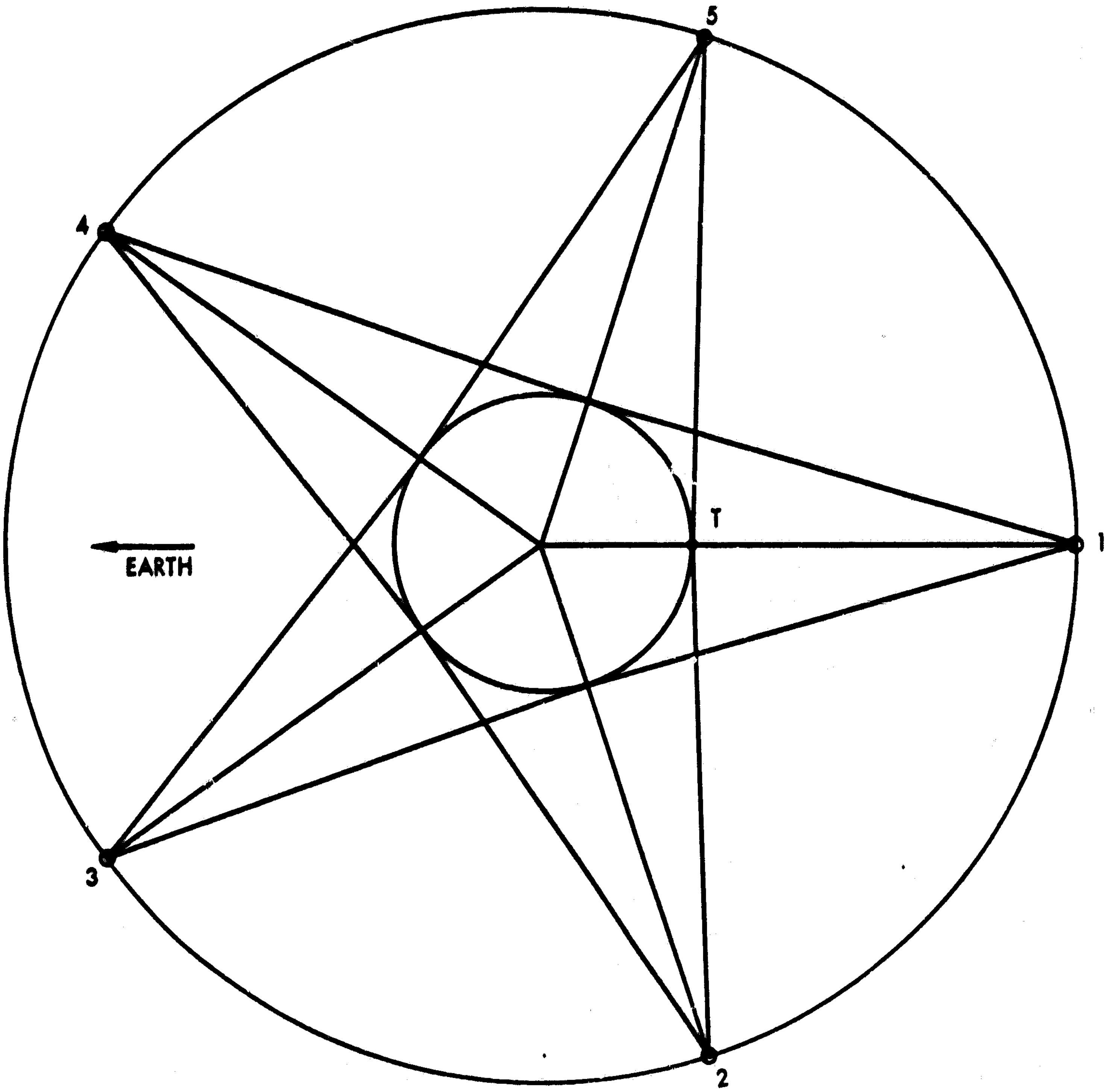


FIGURE 15. FIVE SATELLITE SYSTEM-EQUATORIAL ORBIT

3.5 A POLAR SYSTEM OF LUNAR COMMUNICATIONS SATELLITES

An equatorial system of lunar communications satellites cannot provide coverage for the lunar polar regions. This limitation may be directly overcome by utilizing systems of polar orbiting satellites. There are some special coverage requirements caused by the fact that the moon may occult the line-of-sight path between the active satellite and an earth station for certain fractions of lunar cycle. This occultation is illustrated graphically in Figure 16, where for simplicity, two orthogonal polar orbits are shown for the communications satellites. In the neighborhood of positions A and C, satellites in polar planes 1-1' will be occulted by the moon, while in the neighborhood of positions B and D, satellites in orbital plane 2-2' will be occulted.

As in the case for an equatorial system of satellites, it is possible to overcome this occultation problem by using five or more equispaced satellites in each orbital plane. For orthogonal orbits, a minimum of ten satellites would be required for continuous coverage of the entire lunar sphere.

If three orbital planes are established, it would be possible to continuously cover the lunar surface with a total of nine satellites with three equispaced satellites in each plane. The angular separation between orbital planes is clearly a function of the width of the coverage sector for each set of coplanar communications satellites. If the selenocentric angle from the orbital plane to the limit of mutual visibility (i.e., the crossover point for adjacent coverage zones) is ξ_{max} (see Equation 12), then the required plane separation between the orbits is given by

$$\theta_{\substack{\text{plane}\\ \text{separation}}} = 2\left(\frac{\pi}{2} - \xi_{max}\right) . \qquad (13)$$

If the coverage sector is $\pm$ 75 degrees on either side of the orbital plane, then a plane separation of 30 degrees is necessary. Three satellites equally spaced in an orbit of approximately 7200 statute miles altitude (zero degrees grazing angle) will provide this coverage. If a grazing angle at

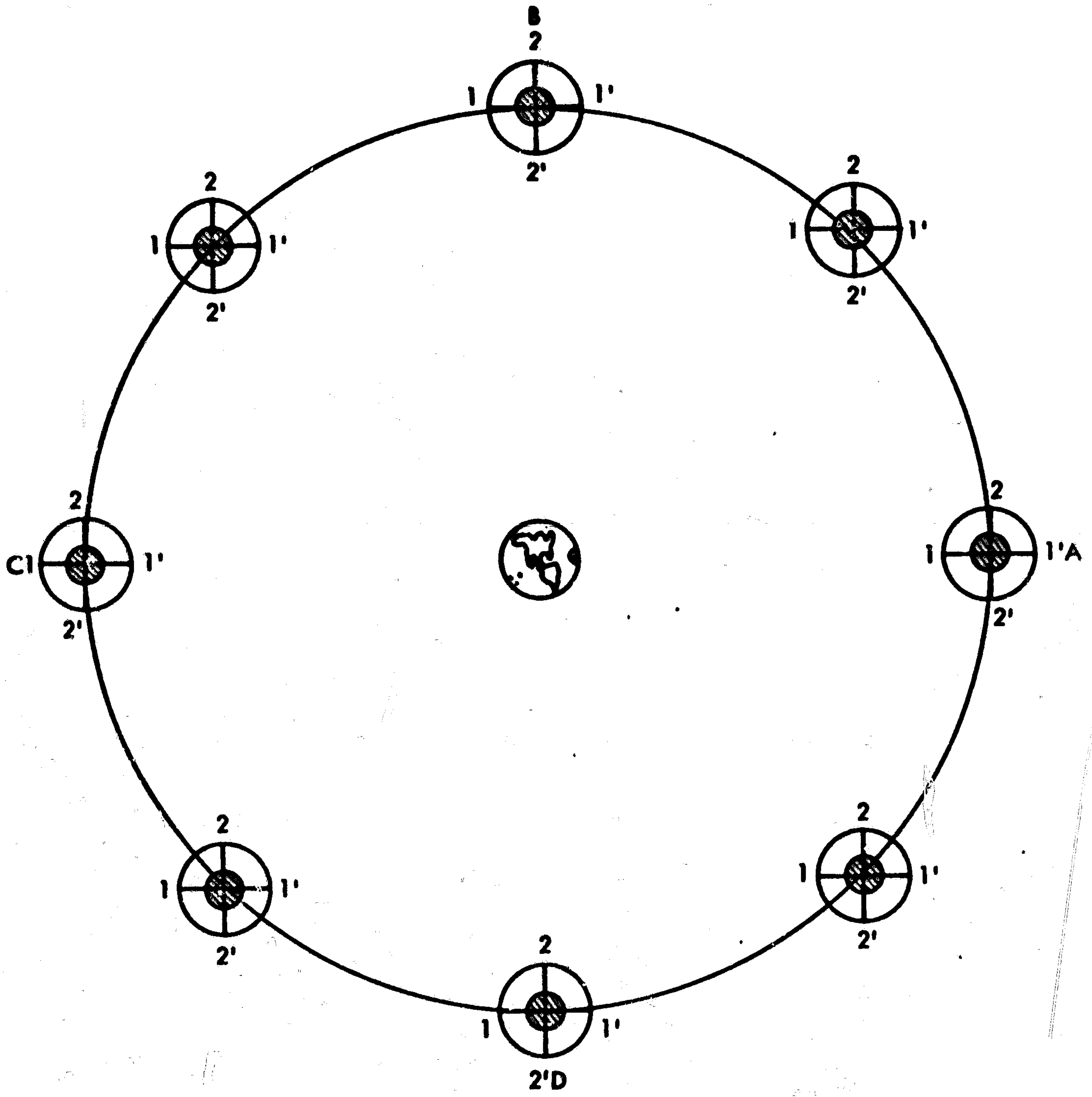


FIGURE 16. POLAR ORBIT ORIENTATIONS

acquisition of five degrees is required, the altitude for a three satellite configuration increases to approximately 23,600 statute miles. As previously noted, these very high orbits should be avoided if long orbital lifetimes are to be achieved. Equally spaced orbital planes would be separated by sixty degrees which corresponds to a coverage sector width of ± 60 degrees from the orbital plane of one set of three coplanar satellites. For an acquisition grazing angle of zero degrees, the required satellite altitude is approximately 3300 statute miles, increasing to approximately 6000 statute miles for a grazing angle of five degrees. Note that sixty degrees is the maximum orbital plane separation for a three orbit system.

As shown in Figure 16 , it is possible to establish lunar polar orbits such that every point in the orbit is visible from any point on earth for large fractions of a lunar cycle. Consider the diagram of Figure which further illustrates the geometry of the lunar communications relay problems. The line 1-1' is the edge of a lunar polar orbit. Note that in lunar position A, satellites in oribt 1-1' would be occulted when passing behind the moon. In lunar position B, all points in oribt 1-1' would just be visible from any point on earth. It is of interest to determine for what fraction of a lunar cycle a polar orbit would be completely visible. If α, β, θ are as labeled in Figure 17 . and R_M is the radius of the moon, R_E is the radius of the earth d_M is the distance from the earth to the moon, and h is the altitude of the satellite, then it is clear that

$$\alpha = \sin^{-1}\left\{\frac{R_M}{R_M + h}\right\} \tag{14}$$

$$\beta = \sin^{-1}\left\{\frac{R_E + R_M}{d_M}\right\}$$

The angle θ is then the sum $(\beta + \alpha)$ and is written as

$$\theta = \sin^{-1}\left\{\frac{R_M}{R_M + h}\right\} + \sin^{-1}\left\{\frac{R_E + R_M}{d_M}\right\} \tag{15}$$

The fraction of a lunar cycle during which all points in orbit 1-1' will not be visible from any point on the earth is

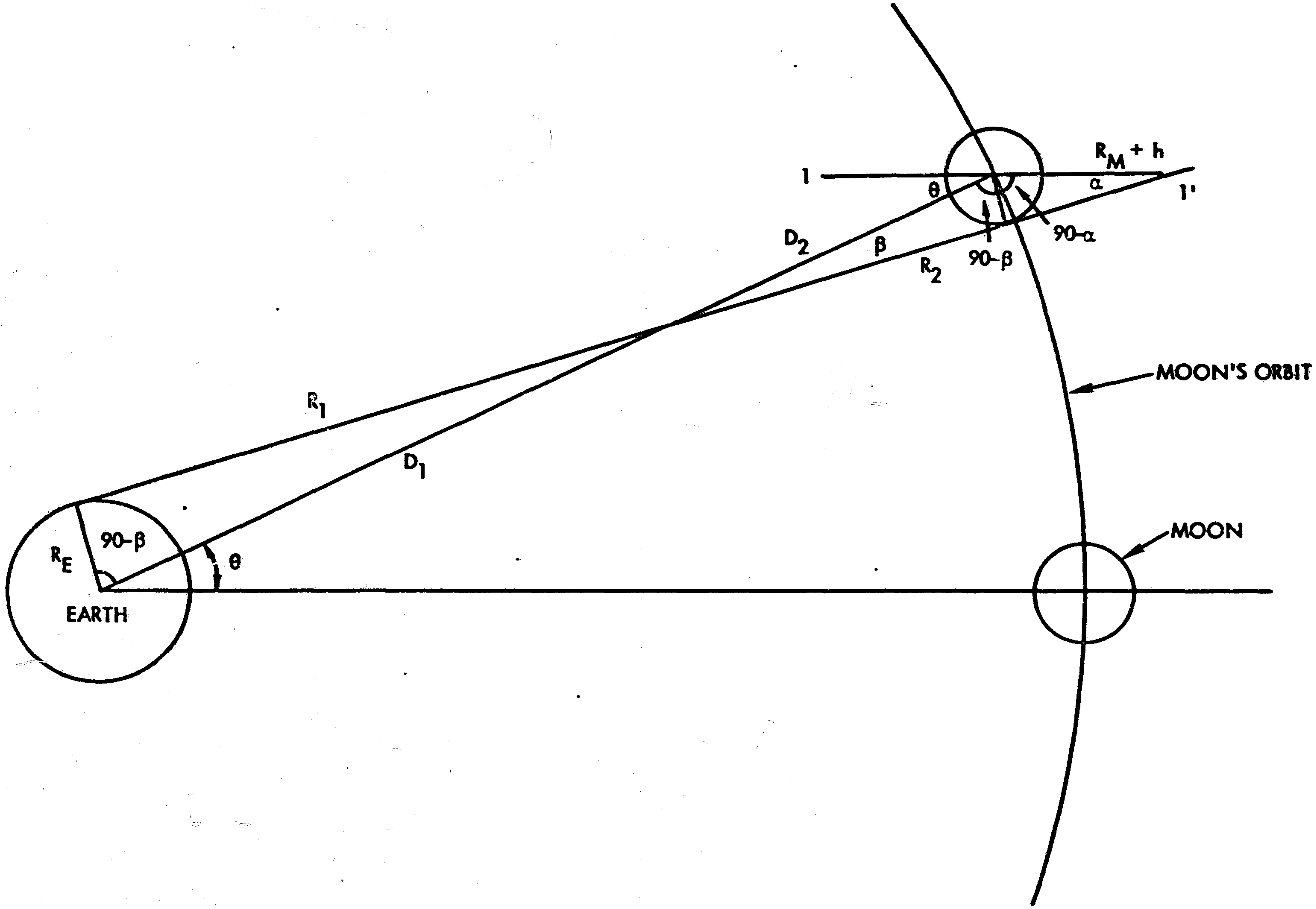


FIGURE 17. ORBIT ORIENTATION DURING OCCULTATION

$$VT = \frac{4\theta}{2\pi} \qquad (16)$$

Noting that the geometry of Figure 17 would be repeated when the moon passes to a point diametrically opposite the position illustrated.

Note also that this visibility factor is strongly dependent upon the altitude of the orbit. Figure 18 illustrates the visibility time as a function of satellite altitude.

3.6 POSSIBILITIES FOR PARTIAL COVERAGE

The preceding discussions on equatorial and polar orbiting systems of lunar communications satellites has emphasized continuous coverage of the complete lunar sphere. While this complete coverage would be a firm long term requirement for comprehensive lunar exploration, the current pace of Apollo missions would allow the establishment of systems for partial coverage.

From an economic point of view, it would be desirable to initially establish the minimum number of relay satellites which could support the projected Apollo G, H, and J type missions. The basic characteristics of these missions are summarized in Table 1.

The fundamental problem is thus to provide communications during the lunar orbit and surface stay phases of an Apollo mission. Other longer term relay requirements resulting from Apollo missions might include relay of scientific data from surface experiment packages left on the lunar surface.

The simplest situation one might consider is that of a single satellite which would be positioned to be mutually visible from earth and lunar stations during the mission. The absolute minimum coverage acceptable would be from the initiation of the lunar descent phase until insertion of the LM on the ascent trajectory. As indicated in Table 1, this phase would be substantially in excess of 35 hours, the surface stay time for G - H type missions. For Apollo 11, the period between the undocking maneuver prior to LM descent and the docking after LM ascent was approximately 28 hours, of which lunar surface stay accounted for approximately 22 hours. This surface stay increases to about 78 hours for J type missions. Thus, if a lunar far side exploration mission were based on G - H type missions, the single communications

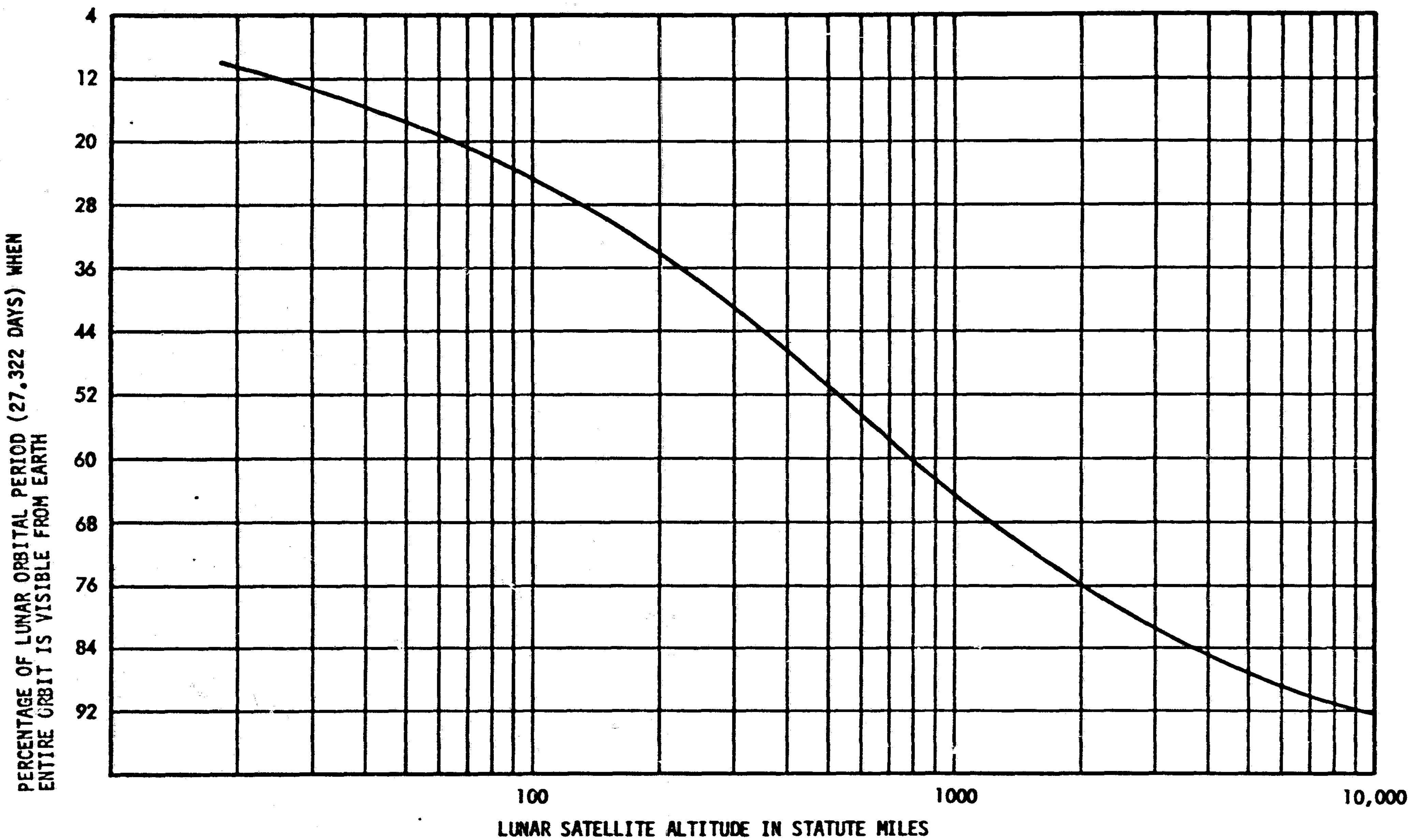


FIGURE 18. VISIBILITY FACTOR FOR LUNAR POLAR ORBIT

relay satellite must be mutually visible by earth LM and CSM for approximately 40 hours, this figure increasing to about 82 hours if J type mission were undertaken.

Consider the situation illustrated schematically in Figure 19 Simplifying assumptions are

(1) Lunar rotation is negligible during satellite passage from acquisition to loss of communications (i.e. from horizon to horizon).
(2) Surface terminal is in plane of orbit.
(3) Orbit is polar and positioned so as to be visible from earth during mission time.

It is clear from the diagram that the total time when relay communications will be possible will be given by

$$\tau = \frac{\theta_{ca}}{2\pi} T \qquad (17)$$

where θ_{ca} is the control angle traversed by the relay satellite as it moves from horizon to horizon, and T is the orbital period of the satellite. Using the laws of sines, θ_{ca} may be found to be

$$\theta_{ca} = \pi - 2\varepsilon - 2\sin^{-1}\left\{\frac{R_M}{R_M + h}\right\}\cos\ \varepsilon \qquad (18)$$

where h is the satellite altitude, R_M is the lunar radius, and ε is the elevation of the satellite above the lunar horizon at acquisition.

Figure 20 illustrates the graph of orbital period in hours versus satellite altitude and shows on the same plot the visibility time for a single satellite. Note that for satellite altitude less than 10,000 miles above the lunar surface, the satellite will be visible for less than 28 hours. This visibility time is insufficient to support on Apollo type far side lunar exploration missions.

It should also be noted that the influence of earth and sun were neglected in the determination of orbital period for the relay satellite. At the higher altitudes, these effects become important. It is probable

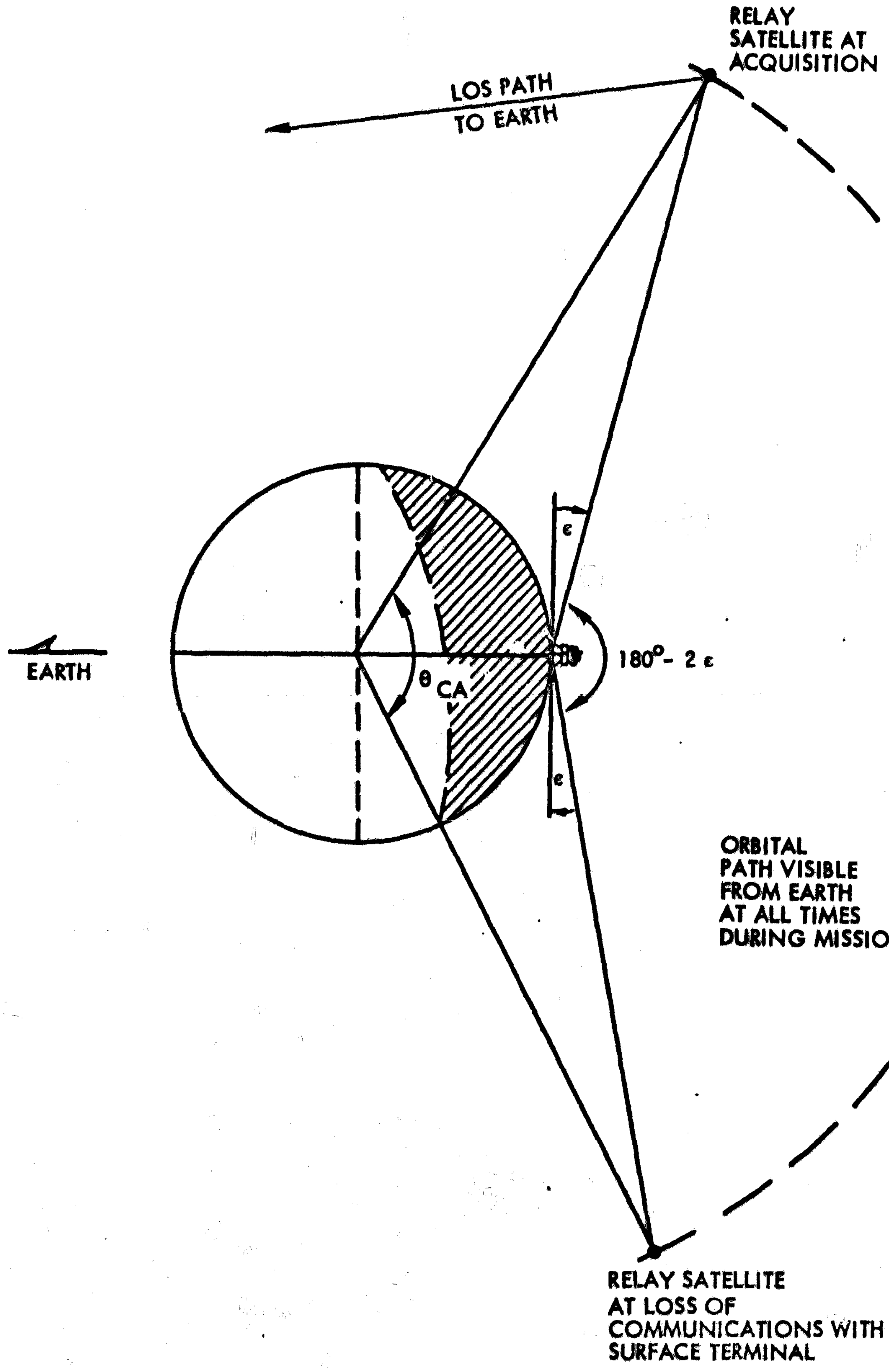


FIGURE 19. VISIBILITY GEOMETRY FOR SINGLE SATELLITE

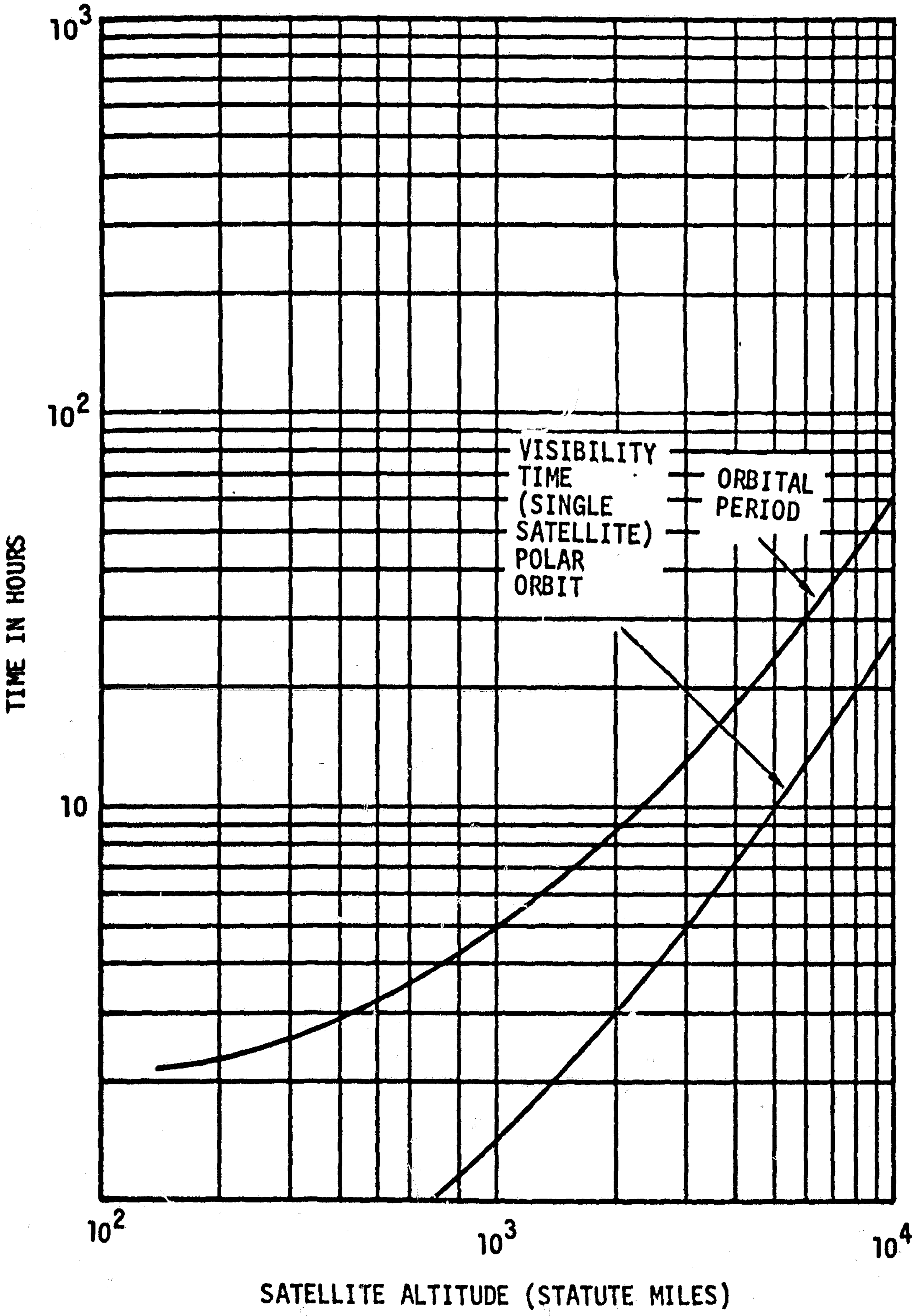


Figure 20. Visibility Time and Orbital Period for Single Satellite

that altitudes greater than 10,000 miles may not be usable.

3. 7 A MINIMUM FULL COVERAGE COMMUNICATIONS SATELLITE NETWORK FOR A SPECIFIC APOLLO TYPE MISSION

The minimum communications network which could provide continuous coverage during an Apollo type mission is a system of three equispaced satellites in polar orbit. It is clear that the orbital plane of these satellites must be properly positioned relative to the earth-moon line. This positioning constraint is illustrated graphically in Figure 21. In this diagram the moon's orbital plane is in the plane of the paper. Three communications satellites are equally spaced in circular polar orbit, the edge of which is illustrated. Note that the invisible region is only on the lunar far side since the near side will be completely visible from earth. The orbital plane of the communications satellites would be adjusted with respect to the earth moon line so that all points of the communications satellite orbit would be visible from earth for the maximum length of time from initiation of the terminal phase of a lunar mission.

Note that if the selected landing site for the mission falls within the invisible region, the orbital plane would be positioned such that the landing zone would be passing into view. If the landing site is within the visible region, there is no contraint imposed upon the orientation of the orbit rather than the previously discussed visibility from earth.

This continuous coverage is, of course, specific mission oriented. Later missions would either have to be properly timed with respect to be original mission for which the satellite network was established, or the network could be repositioned. The advantages of establishing such a single three satellite system are:

(1) Basic coverage for Apollo missions is possible.

(2) It allows for a time phased establishment of a full coverage system.

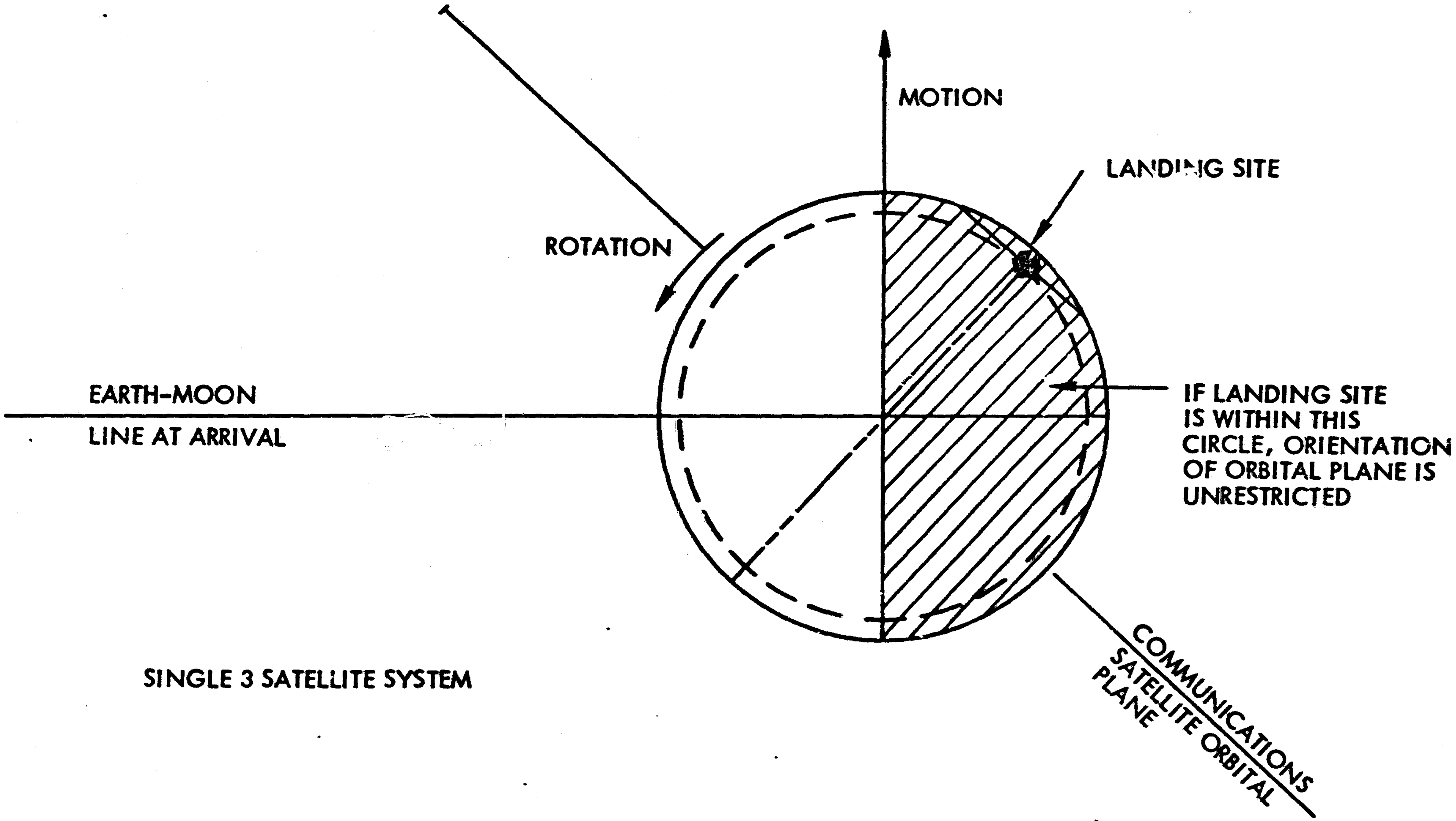


FIGURE 21. EFFECT OF LANDING SITE ON ORIENTATION OF SATELLITE ORBIT

4.0 SUMMARY AND CONCLUSIONS

The coverage and visibility analysis summarized in this report is based on two basic ground rules:

(1) Continuous coverage of the full lunar sphere should be the long term goal for a lunar satellite communications system.

(2) The communications relay mode is assumed to be a two way earth-relay satellite-lunar terminal mode. No satellite-satellite relay capability is assumed.

For continuous coverage of the entire lunar sphere, the minimum network of relay satellites is composed of three sets of three polar orbiting satellites. The satellites are equally spaced in circular orbit, and the orbital plane separation between adjacent orbits ranges from thirty to sixty degrees. The sixty degree separation is most desirable in that satellite altitudes are considerably less than those required for the thirty degree separation.

If only two orbital planes are established, ten satellites are required for full continuous coverage. Five satellites would be equally spaced in each of two orthogonal circular orbits. These orbits may both be polar, or one polar and one equatorial.

Full coverage is not possible from equatorial orbit. For continuous coverage of an equatorial sector, five satellites equally spaced in equatorial orbit are required.

The most attractive possibility for partial coverage is a network of three equally spaced satellites in circular polar orbit. It is shown that such an orbit may be positioned to provide continuous coverage for a specific mission whose landing site and mission time are known during substantial fractions of a lunar cycle. Such a network is a member of the minimum network of nine polar orbiting satellites required for continuous coverage of the entire lunar sphere. Therefore, the full network may be established over a period of time, this time depending upon the evolution of operational requirements. It might develop that a single three satellite network would serve to support a wise variety of Apollo type missions if the missions were properly timed.

Single satellites (other than the libration point satellite) cannot provide continuous coverage for an Apollo mission. Two satellite networks increase coverage time for an Apollo type mission, but cannot provide complete coverage.

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